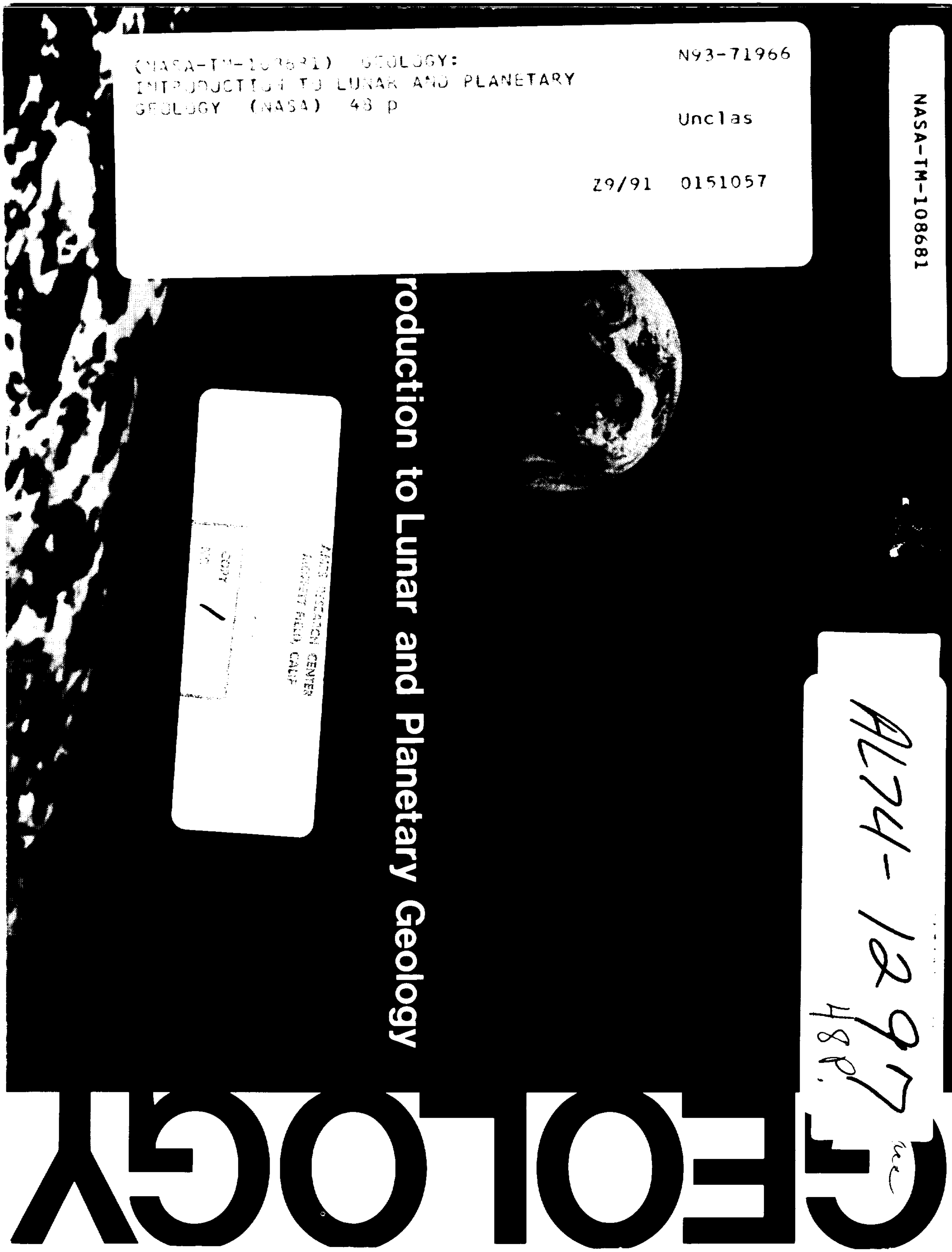
roduction to Lunar and Planetary Geology
GEOLOGY

Introduction to Lunar and Planetary Geology

by
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Public Affairs Office Publication.

Foreword

This booklet has been prepared to acquaint the reader with the relatively new field, *Planetary Geology*—the study of the geology of the Moon and planets. It is divided into four parts; Part I discusses some of the basic principles of physical geology—principles that are applicable not only on Earth, but on the Moon and planets as well. Part II introduces the methods that are employed in studying the geology of a planetary body where "field work" is non-existent, or at best, extremely limited (can you imagine attempting to decipher the geology of the Earth from less than a half dozen "Earth-landings"?). Part III is a brief account of the geology of the Moon and Part IV, the geology of Mars. An appendix lists general and special references on geology and planetary geology and provides sources of maps and photographic materials.

Obviously, this booklet is not a complete treatment of the subject. The intent is to create an *awareness* and some appreciation for the importance of geological processes.

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Ronald Greeley, 1972
University of Santa Clara

PART I Instant Geology

INTRODUCTION

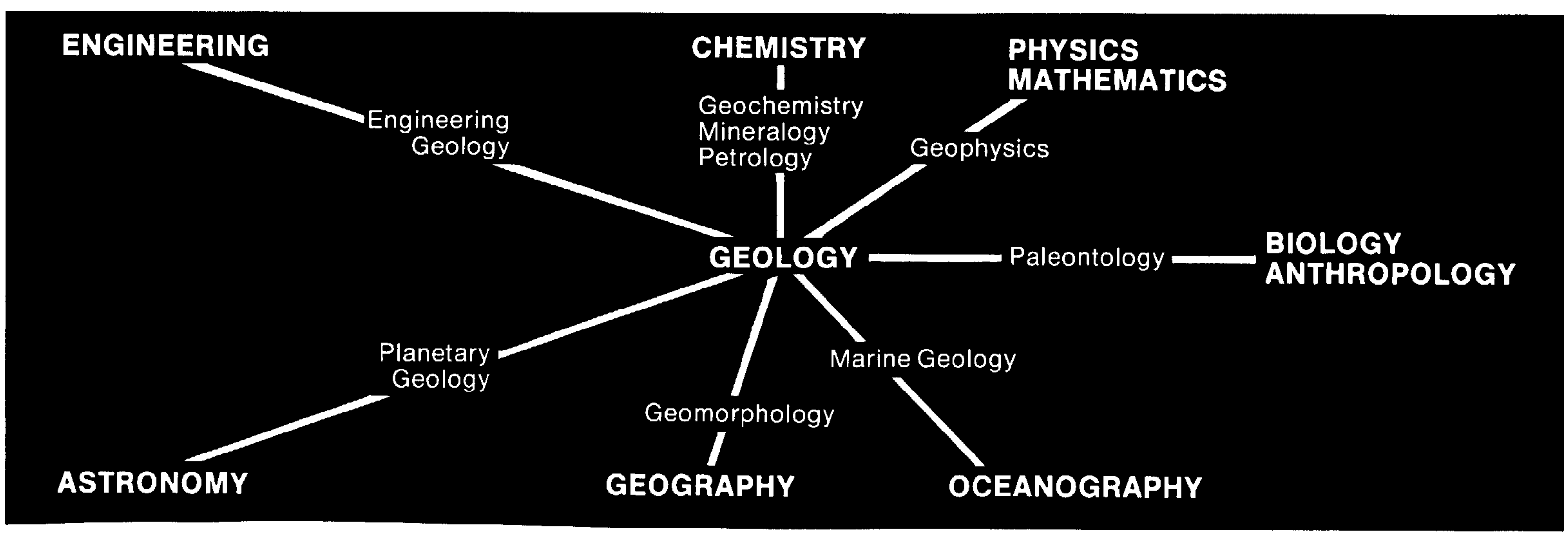
This section presents some of the basic concepts and principles of physical geology. Geology (*geos* = earth + *ology* = study) is the study of the origin, composition and structure of the Earth and the processes that shape it. The term *Planetary Geology* (or Extraterrestrial Geology or Astrogeology) is applied to the geology of the Moon, Mars, and so on.

Most scientific fields are interrelated. Geology is related to other sciences through its subdivisions.

As in all scientific fields, the guiding principle in geologic investigations is the *scientific method*, the logical sequence of experimentation, observation, deduction and the formulation of hypotheses, theories and laws upon which our body of scientific knowledge builds.

The Earth is subdivided into three units:

1. Atmosphere (Nitrogen - 75%, Oxygen - 25% + water, carbon dioxide, inert gases, and dust)
2. Hydrosphere (water covers about ¾ of Earth's surface, 70% by the oceans + 5% by other bodies of water)
3. Lithosphere (*litho* = rock), made up of an outer crust (solid), mantle (plastic) and core (liquid and solid parts). Oxygen, Potassium, Sodium, Calcium, Silicon, Aluminum, Iron, and Magnesium are the most abundant elements in the crust, and therefore, most of the rocks and minerals in the crust are composed of these elements.



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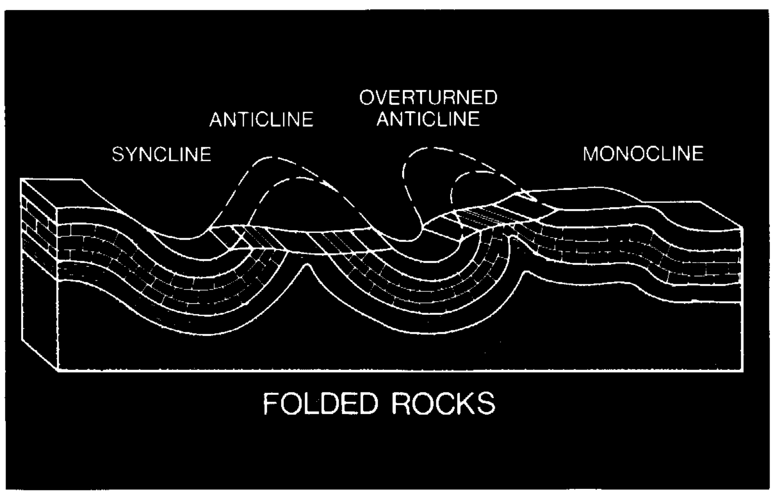
GEOLOGICAL PROCESSES

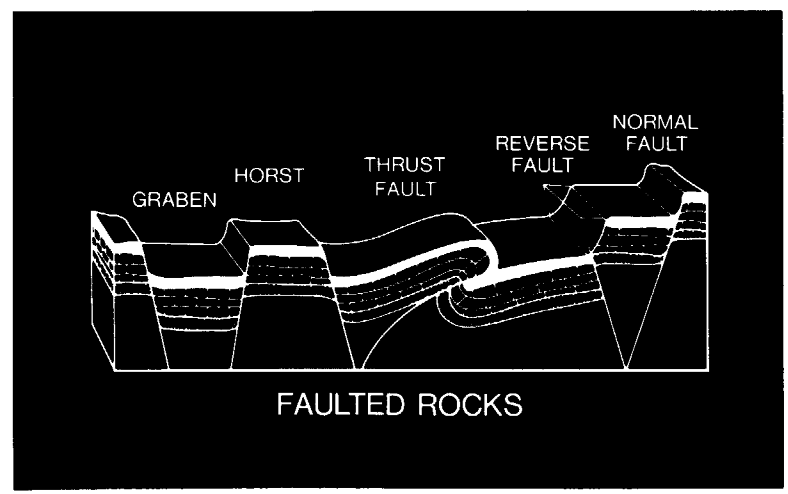
The Earth is a dynamic, ever-changing body, as evidenced by the three main processes that shape its surface: gradation, igneous activity, and diastrophism. *Gradation* is the complex process of weathering rocks by disintegration and decomposition so that they can be eroded, transported and deposited in other areas. Gradation acts through the agents of water (streams, oceans, glaciers, etc.), wind, and gravity (landslides, avalanches, etc.). Weathered rock that is being transported by these agents will usually be deposited wherever there is a decrease in velocity of the transporting medium. Thus, deposition occurs where streams enter lakes or other relatively still bodies of water, sometimes forming deltas. Once the rock particles are deposited, they may be changed to rock, or *lithified*. If the newly formed rock body is large (at least several square kilometers) it is called a *formation*, the basic unit of geologic mapping. A formation is a body of essentially the same kind of rock that is large enough to be shown on a large scale map (about 1 inch to the mile).

As deposition continues through geologic time (10s, 100s, 1000s, millions of years) successive formations are built on top of each other. The formation on the bottom of the sequence must be the oldest because it was deposited first; the formation on the top must be the youngest because it was last deposited. This rather obvious and simple — minded relationship forms one of the basic tenets in geology: *The Law of Superposition.*

Igneous activity, the second process in geology, is the movement of molten material, called *magma*, within the crust and the formation of igneous rocks. *Volcanism* is one form of igneous activity that involves the extrusion of magma at or near the surface of the crust. Lava flows, volcanoes, geysers and hot springs are all forms of volcanic activity. On the other hand, magma that pushes through the crust but cools before reaching the surface constitutes the second kind of igneous activity, *plutonism*. Rocks formed by plutonic activity, such as the granites of the Sierra Nevada, are characterized by their large, interlocking mineral grains.

Diastrophism is the third major geological process. It involves the movement of solid and plastic rocks within the lithosphere. Earthquakes, faulting, and rock tides are examples of diastrophic phenomena. Rocks may deform plastically to form folds (anticlines, synclines, etc.) or they may shear, or break, through faulting. At least in part, diastrophism is the result of major shifting of crustal and mantle materials.





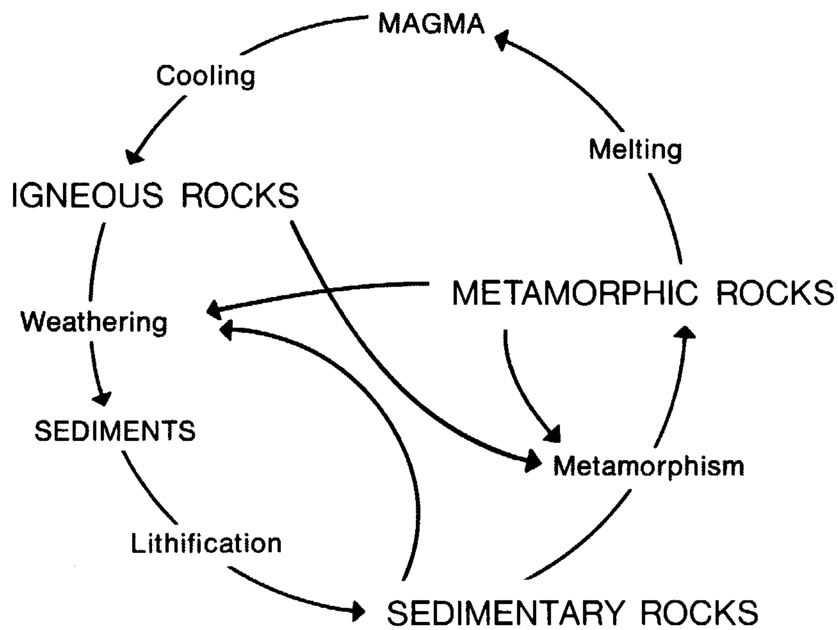
Diagrams illustrating some of the results of *diastrophism*, or the deformation of rocks. In the left diagram the rocks have folded and the surface eroded: in the right diagram they have sheared, or broken along faults.

ROCK CLASSES

The terms *rocks* and *minerals* are often used interchangeably, but to do so is incorrect. Minerals are naturally occurring inorganic solids of fairly consistent chemical composition. Each mineral species has a unique internal crystal structure that is governed by the arrangement of the chemical elements making up the mineral.

Rocks, on the other hand, are usually composed of aggregates of one or more minerals. For example, if several specimens of the *mineral* quartz were crushed to particles the size of sand grains and the grains cemented together, then the *rock*, sandstone, would be formed. Or, if magma (molten parts of the crust of the Earth) containing the elements silicon, oxygen, iron, magnesium, potassium, and aluminum in the right proportion and under certain conditions, were allowed to cool, then the magma would solidify by the elements combining chemically to form individual mineral grains of quartz, feldspar and biotite (mineral species). Taken together, they would constitute the *rock*, granite.

The major categories of rocks making up the solid crust of the Earth result from the three geological processes. In gradation, existing rocks are broken into small particles or taken into solution by weathering and erosion so that they can be transported and settled out as deposits. The deposited rock particles can be lithified to form *sedimentary rocks*. *Igneous rocks* (literally "fire formed") result from cooling and solidification of magma beneath the surface through plutonism, or on the surface from volcanism. High temperatures and pressures associated with diastrophism and igneous activity can metamorphose (change) existing rocks to form *metamorphic rocks*. The relationships of one rock type to another, as well as the processes involved, can be seen in *The Rock Cycle*.



THE ROCK CYCLE

LAW OF UNIFORMITY

The processes operating to shape the Earth can, for the most part, be observed directly: rain, wind, flowing water, volcanoes, earthquakes. The rocks, minerals, and structures resulting from these processes can be chemically and physically analyzed during and after their formation. The laws of chemistry and physics, usually expressed by mathematics, govern the manner in which the processes operate and the products that are formed. These same processes operated yesterday, last year, in the last century, in the last millenium, and so on back through the hundreds of millions of years of geologic time. This assumption forms another simple truth in geology, *The Law of Uniformity*—the processes operating today must have operated in the past, and will probably continue to operate in the future. In other words, the present is the key to the past and the future.

GEOLOGIC TIME

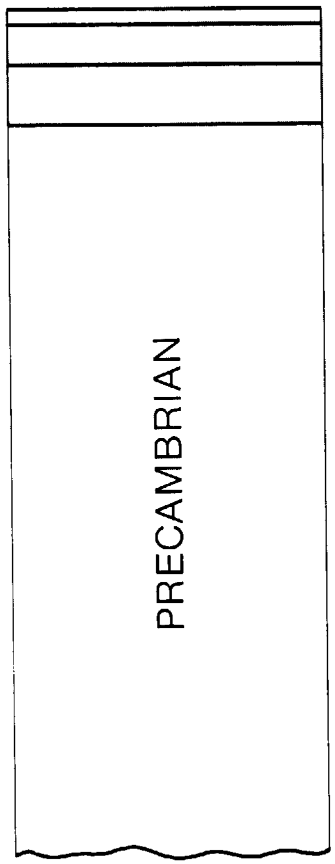
Geologic time is expressed either in *relative ages* or *radiometric ages*. The Law of Superposition makes use of relative geologic time, in which formations are younger or older than other formations with no reference as to how much older or younger (expressed in years) they might be. Nearly all rocks on the surface of the earth can be placed within a relative time scale by applying superposition on a worldwide basis.

Radiometric ages are determined by radioactive "clocks" built into some rocks at the time the rocks are formed. Certain radioactive elements "decay" to other forms (isotopes) or other elements at a known rate (the "half-life" of the element, or the time it takes for half the material to decay). By measuring the quantities of the original or "parent" material and the amount of decay or "daughter" material, it is possible to establish a ratio directly related to the length of time since the rock containing the elements was formed. Only a small part of the rocks on the surface of the Earth contain elements suitable for absolute age determinations. However, by using combinations of relative and absolute age dating techniques it is possible to determine the geologic age of most rocks. These rocks can then be placed in a *Geologic Time Scale*.

The information presented in this section forms the foundation for physical geology. The principles discussed are applicable to all geologic problems and are employed constantly in planetary geology.

GEOLOGIC TIME SCALE

PROPORTIONAL SCALE TIME



ORIGIN OF THE EARTH 4.5-5 BILLION YEARS.

ERA	PERIOD	YEARS AGE (MILLIONS OF YEARS AGO)
CENOZOIC	QUATERNARY TERTIARY	65
MESOZOIC	CRETACEOUS JURASSIC TRIASSIC	225
PALEOZOIC	PERMIAN PENNSYLVANIAN MISSISSIPPIAN DEVONIAN SILURIAN ORDOVICIAN CAMBRIAN	570
PRECAMBRIAN		

PART II Planetary Geology

INTRODUCTION

Questions often asked are, "Why study the geology of the Moon? What good can it do us here on Earth?" Considering the resources that have been invested in planetary geology, these are valid questions that should be asked . . . and answered. The National Academy of Sciences placed three national goals before the scientific community: 1) determination of the origin and evolution of the Solar System, 2) determination of the origin and evolution of life, and 3) clarification of the nature of the processes shaping Man's earthly environment. These are objectives that have been sought for hundreds of years; it is only through the possibilities of manned and unmanned space travel that these goals are now within our reach. In addition to the aesthetic and "pure science" (knowledge for the sake of knowledge) considerations, there are economic and environmental aspects of planetary geology which bear directly on our day-to-day lives.

Many fundamental geological problems on Earth could be solved by detailed comparisons with other planets where the relative effects of different sizes, compositions and atmospheres on the evolution of the planet could be assessed. For example, very little is known of the early history of the Earth. Only the last 0.5 billion years of our estimated 5 billion year history is readily available for study because so much of our planet is covered by water and the remainder is constantly attacked and altered by weathering and gradation processes. On the other hand, because the Moon has no eroding atmosphere and the crust apparently has been stable for several billion years, it displays a surface that is commonly five to eight times older than most of Earth's surface. In this older surface is locked (but available for study) the early history of the Moon and possibly the Earth as well.

Many of the questions regarding the origin and evolution of the Solar System are centered on the chemistry of the final accretion of the Sun and planets, and the distribution of the elements among the planets. Analyses of returned samples, geologic interpretation of planetary surfaces and geophysical studies of planetary interiors are providing many of the answers to these questions. These same considerations are of utmost importance to the biologist seeking the origin and evolution of life. He must know the kinds of rocks and minerals on planetary surfaces (including Earth), as well as the geologic environment and processes modifying those surfaces. He must know the conditions in the geologic past as well as the present.

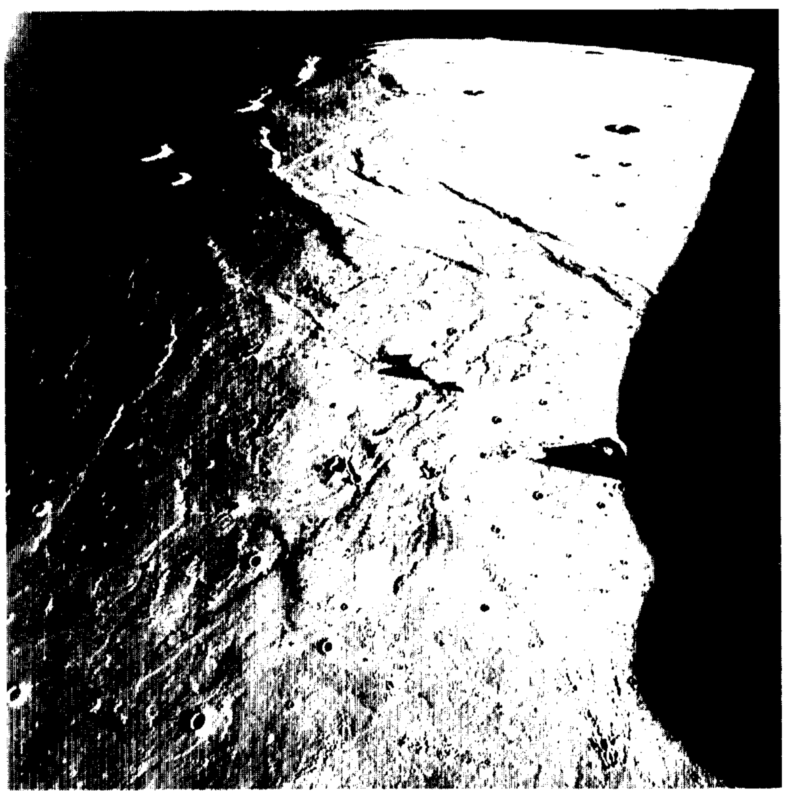
Of more immediate concern, planetary geology can contribute to the solution of economic and environmental problems of Earth. For example, a better understanding of core-mantle-crust relationships and the formation of magma through comparisons with other planets may help in understanding the formation of mineral-containing ore bodies on Earth. Perhaps by knowing the evolution of different planetary atmospheres and the influence of those atmospheres on surface procésses, a better understanding can be gained of our own complex atmosphere and hydrosphere. Then perhaps, more effective means can be found to reverse the ever-increasing pollution and degradation of our habitat.

METHODS IN PLANETARY GEOLOGY

Planetary geology can be approached from several disciplines: 1) *stratigraphy* (geologic mapping), 2) *structural geology* (study of individual features and their origin), 3) *petrology* (study of planetary composition), 4) *geophysics* (study of the dynamics of planets).

STRATIGRAPHY

Geologic mapping involves subdividing surface and near-surface rocks into different formations according to their type and age. On Earth, geologic mapping is a combination of field work and laboratory studies of rocks and aerial photographs. In planetary geology, mapping must be done primarily by remote sensing methods—mostly interpretation of aerial photographs (field work is rather costly and not always practical!). Several different techniques have been developed to make geologic maps of the Moon. With proper modifications to account for differences in environments, these same techniques will be used to map some of the other planets. These techniques include the application of superposition, crater frequency studies, geomorphology of surface features, and color and albedo of surface materials to differentiate formations.



Superposition

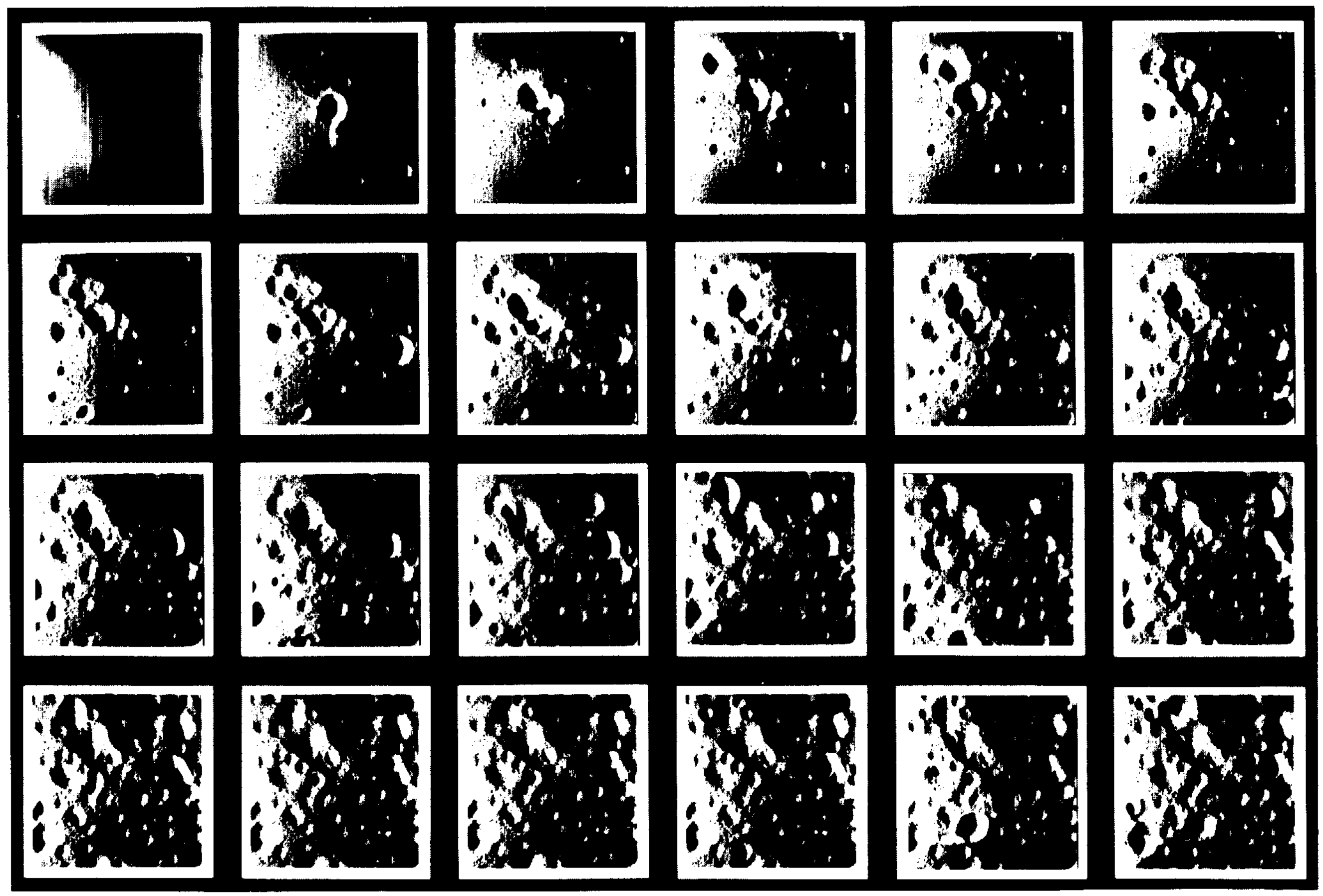
Superposition is a very useful means to separate geologic formations. For example, the material thrown out of an impact crater during its development is composed of broken rock fragments called *ejecta*. The *ejecta blanket* makes a formation that is *superposed* on the pre-crater surface and can be identified on aerial photographs and mapped. On some lunar photographs, individual lava flows are visibly superposed on older flows. These, too, can be identified and mapped as separate geologic formations.

Multiple lava flows in Mare Ibrium. By *superposition*, Flow 3 is oldest, Flow 1 is youngest and Flow 2 is intermediate in age (Apollo 15 Metric camera frame M3-1557).

Crater Frequency

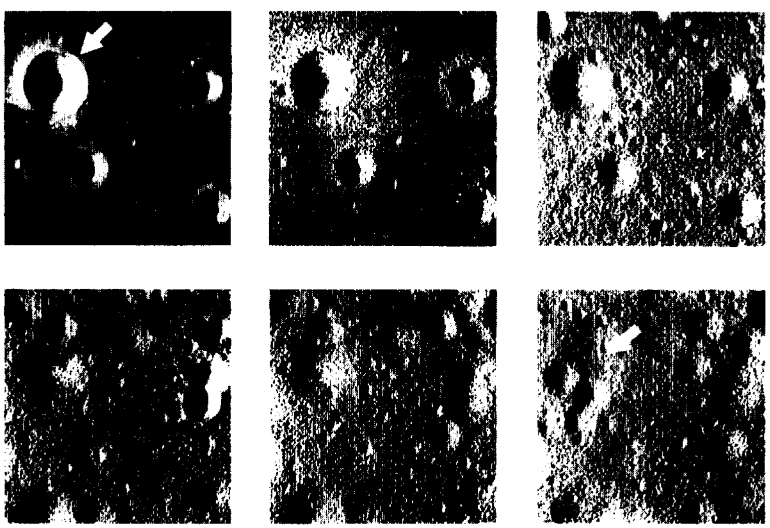
There is good evidence to show that most of the lunar craters are of impact origin, *i.e.*, they were formed by meteorites or other planetary bodies striking the surface. As time passes any single formation (such as a fresh lava flow) will have progressively more and more craters because it is subjected to meteoritic impact for a progressively longer period of time. By counting the craters on individual surfaces, it is possible to establish relative ages for those surfaces. A formation with abundant craters is most likely older than a formation with few craters.

Time-lapse sequence from laboratory simulation illustrating the transition from a smooth, plane surface to a surface blanketed with impact craters (courtesy of D. E. Gault).



Geomorphology

The technique of using geomorphology to distinguish geologic formations is related to crater frequency studies. Meteoritic erosion, or the bombardment of surfaces with thousands of meteorites, progressively wears away sharp features to produce rounded features. A fresh impact crater has sharp, well-defined rims; with time the rims are worn away until they are barely discernible. Depending upon its size, the crater may even eventually disappear (larger craters, however, tend to remain). Geomorphology, or the degree of sharpness of craters on a surface, indicates the relative age and distribution of the formation containing the craters. Craters of the light-colored highlands on the Moon are degraded in comparison to the sharp craters of the dark lowlands, indicating a difference in age between the two areas.



Geomorphic stages in crater modification by meteoritic erosion; crater (arrow) initially has sharp rim, then is progressively degraded until it nearly disappears (courtesy of D. E. Gault).

Color and Albedo

Color and albedo are properties of formations that are commonly employed in geologic mapping. Obviously, different rocks may have different colors. Accurately determining the color of planetary surfaces gives additional clues for distinguishing different formations. Albedo refers to the reflective properties of surfaces. Different units can be identified and mapped by measuring the reflectance of light from different planetary surfaces.

Geologic mapping is accomplished through a combination of techniques employing superposition, crater frequencies, geomorphology, color and albedo—all properties that can be determined by remote sensing. Small scale geologic maps (1 cm to 10 km*) have been made for nearly the entire frontside (the side always facing Earth) of the Moon. Large scale maps (1 cm to 50 m) have been prepared for the immediate areas of the Apollo lunar landing sites. Plans for mapping the geology of Mars utilizing photographs returned by Mariner 9 spacecraft are being formulated. These maps will be small scale, covering large areas (1 cm = 50 km).

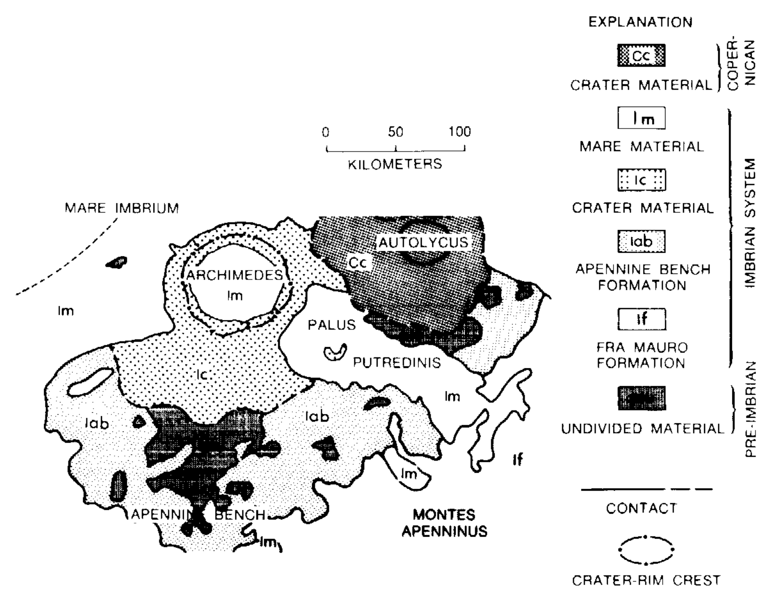
* equivalent to 1 inch to about 16 miles. Metric units are used throughout the booklet: 1 cm (centimeter) = .4 inch, 1 m (meter) = 39 inches, 1 km (kilometer) = .62 mile.

STRUCTURAL GEOLOGY

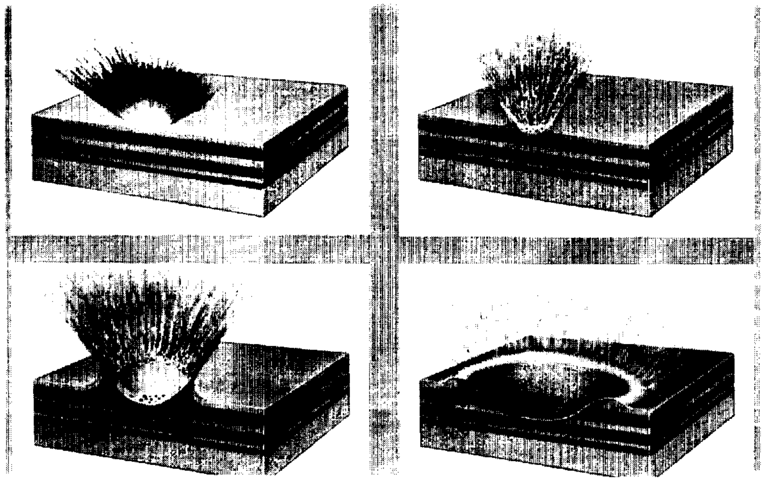
Structural geology involves studying the origin of individual features and determining their relationships to the stratigraphy (shown by geologic maps). The most dominant structures on the Moon and Mars (and probably Mercury) are craters. These planets have virtually no atmosphere, or a very thin atmosphere that allows meteors to impact the surface without burning up. Thin atmospheres cause surface processes to be less effective, thus preserving craters.

Because craters are such dominant features, their study is an important aspect of planetary geology. Crater simulations in the laboratory and field, field studies of natural impact craters, and volcanic craters all aid in the interpretation of lunar and planetary craters and cratering processes.

Structures other than craters are also recognized on planetary surfaces. Faults (breaks in the crust), mountain blocks, meandering channels and domes are features that have been identified on lunar photographs. Similar structures, plus some that are rather unique, have been seen on photographs of Mars. Laboratory studies and field investigations of similar features on Earth help interpret planetary counterparts.

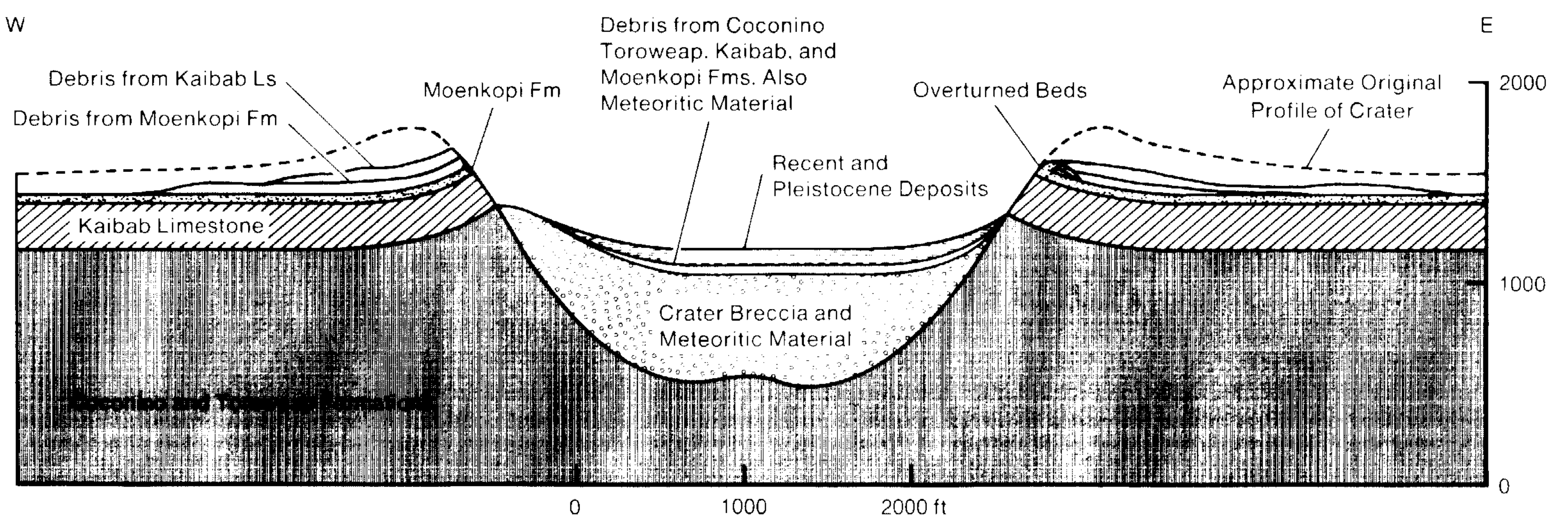


Telescopic photograph and small-scale geologic sketch map of southeastern Mare Imbrium. Patterns and letter-abbreviations designate geologic formations of different rock types and ages ("C" is youngest, "I" is intermediate, and "pI" is oldest). Star indicates Apollo 15 landing site (from Wilhelms, 1970, after Hackman, 1966; Lick Observatory Photograph).



Sequential diagrams to show typical formation of an impact crater and ejecta blanket (debris thrown out of crater): from laboratory simulations at NASA-Ames Research Center.

Aerial photograph and geologic cross section (below) of Meteorite Crater, Arizona. Investigations of natural impact craters are essential in understanding impact processes. (diagram from Shoemaker, 1960).



MINERALOGY

One important objective of planetary geology is the determination of the chemical composition of the planets. Homogeneities and heterogeneities of the planets are directly related to the origin and evolution of the Solar System. For example, Earth's crust is heterogeneous—it is made of chemically differentiated rock types, which indicates that parts of Earth must have gone through a molten stage. On the other hand, a planet composed of the same type of rock throughout may never have gone through a molten stage.

Surface sampling and remote-sensing techniques (infrared spectroscopy, gamma-ray spectrometry, etc.) provide geologic data on the rocks and minerals composing planetary surfaces. These data, combined with geophysical determinations of the internal characteristics of the planets, allows estimates of the internal composition of planets.

GEOPHYSICS

Geophysics is the application of physics to the study of planets to learn their structure, and dynamics, and the physical conditions of their interiors. This is accomplished through several diverse methods, including the measurement of heat flow from the planetary interior, mapping magnetic and gravity fields, and determination of seismic activity. Of importance also is the determination of the size, shape, mass and rotational characteristics of the planets. Some of these measurements can be made by Earth-based instruments. Other measurements must be obtained directly on the surfaces, or very close to the planet. This is accomplished by sending spacecraft to the planets as fly-bys, orbiters, or landers.

Although these major lines of geologic study (stratigraphy, structural geology, mineralogy, and geophysics) have been presented separately, in practice each complements the other in building a coherent and meaningful interpertation of the geology of a planet.

PART III Geology of the Moon

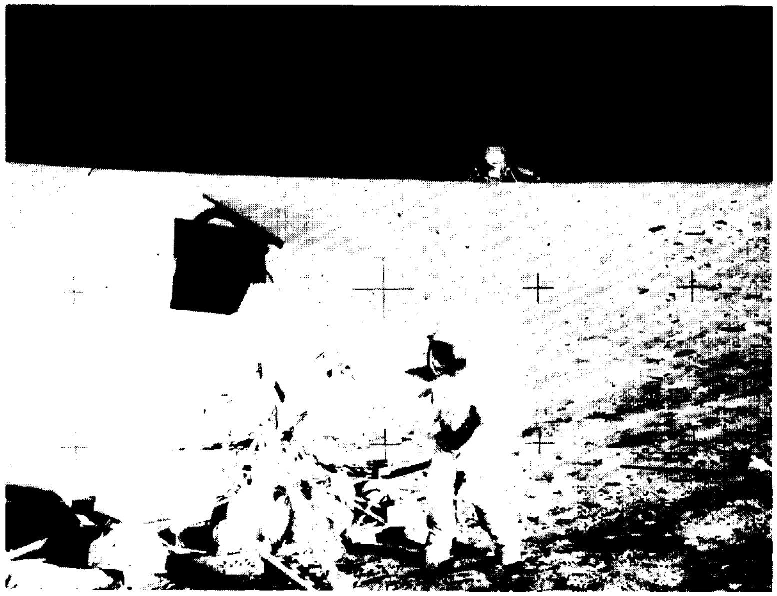
INTRODUCTION

Most of the techniques and methods of planetary geology are the results of the efforts of geologists and other scientists of the Astrogeology Branch (U.S. Geological Survey), NASA research centers, and universities. These techniques evolved primarily through studies of the Moon.

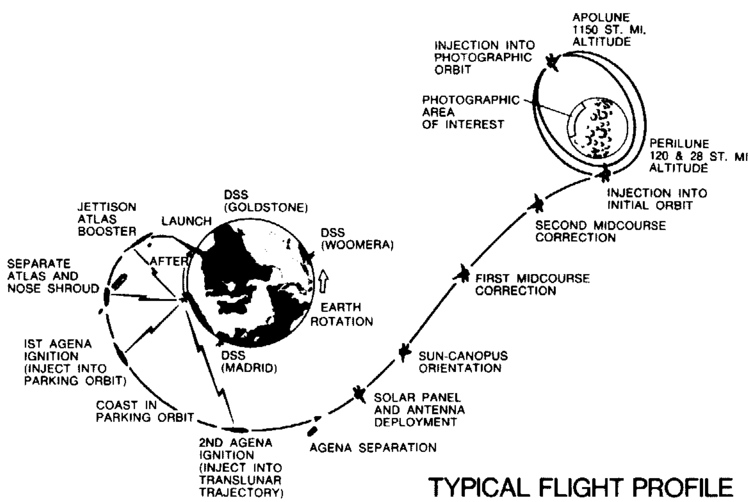
Serious observations of the Moon began when Galileo first turned his telescope skyward. Even with improvements of the telescope through the present, however, investigators are limited in the data that can be obtained from Earth. When the decision was made to send a man to the Moon, it became apparent that more data were needed for successful missions than could be obtained from Earth. A series of unmanned spacecraft preceded Apollo through the 1960s. These included *Ranger*, *Surveyor*, and *Lunar Orbiter*; all had the ability to make pictures of the lunar surface; some could analyze the lunar soil to determine its composition and engineering properties. The data from these missions will provide study material for many years.

However, there is no substitute for human observation. Apollo missions to the Moon have provided detailed and direct observations of the lunar surface, both on the ground and from the orbiting command module. Returned lunar samples have given a better understanding of the geologic setting for the major formations and the chemical evolution of the Moon. Apollo photographs are providing details of the surface never seen by unmanned spacecraft.

Manned and unmanned missions to the Moon are allowing geologists to mold a comprehensive interpretation of the origin and evolution of our first "foreign" planetary body, the Moon.



Astronaut Bean and two U.S. spacecraft on the Moon. Surveyor 3, in foreground, is an unmanned spacecraft which had landed 2½ years earlier. The LEM is about 183 m distance on the horizon (Apollo 12 frame 48-7133).

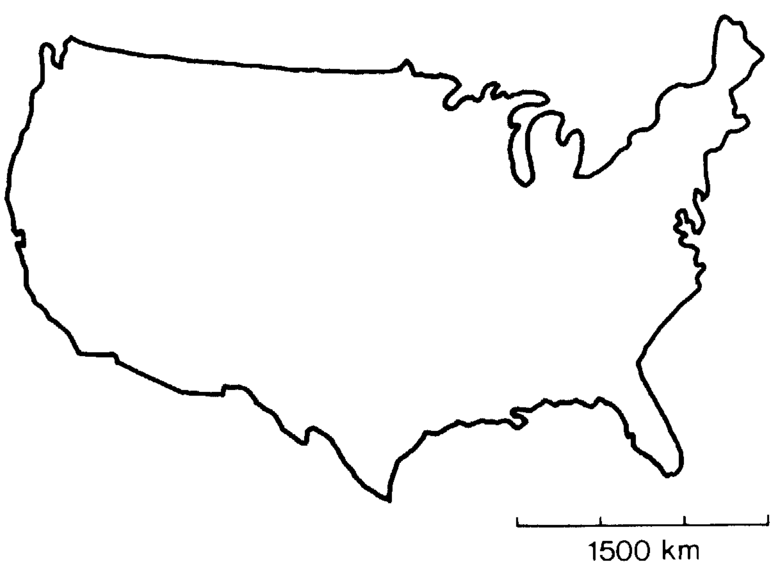


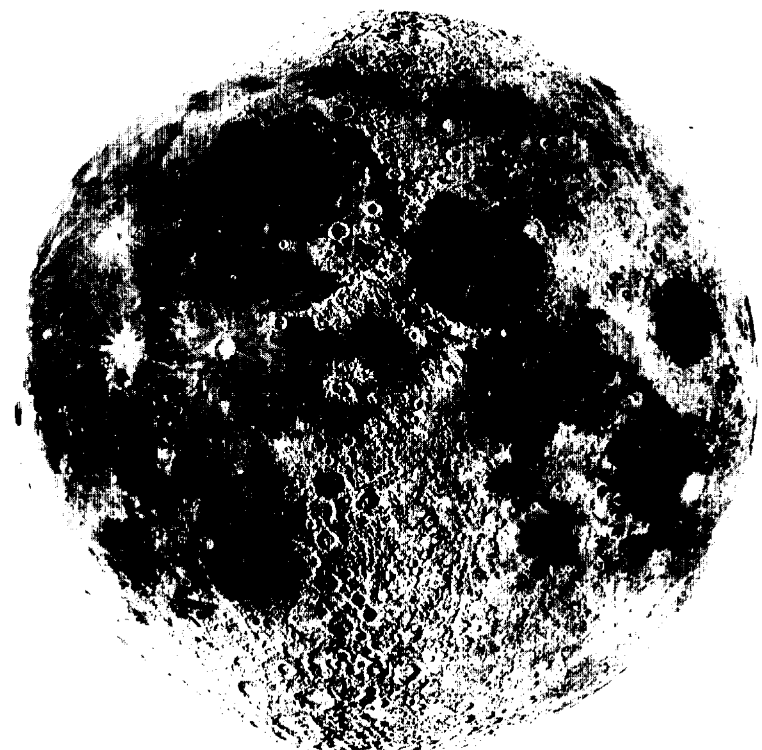
Typical flight profile for an unmanned lunar mission (NASA diagram 66-H-1047).

EXERCISE

Before proceeding with this very brief summarization of lunar geology, please do the following exercises to become familiar with the features and geography of "the face of the Moon".

The Moon is 3476 km in diameter. To gain an appreciation of its size, draw a circle representing 3476 km on the map of the United States, using the star as the center of the circle. Earth's moon is large in comparison to its "parent" planet; the moons of Mars, for example, are only about 8 and 22 km in diameter, much smaller than the star on the map of the United States.





Lick Observatory Photograph

The following questions refer to the composite full-disk photograph of the Moon on the preceeding page.

1. Is the surface of the Moon homogeneous, that is, is it composed of material that appears to be the same everywhere?

2. In your opinion, what aspect of the Moon is the most noticeable?

3. If you had to separate the different areas of the Moon into two main categories (for example, continents and oceans on Earth), what would these categories be? List the characteristics of each category:

Category A	Category B

4. What physical properties of the lunar surface (that can be distinguished on the photographs) did you employ in characterizing the areas above?

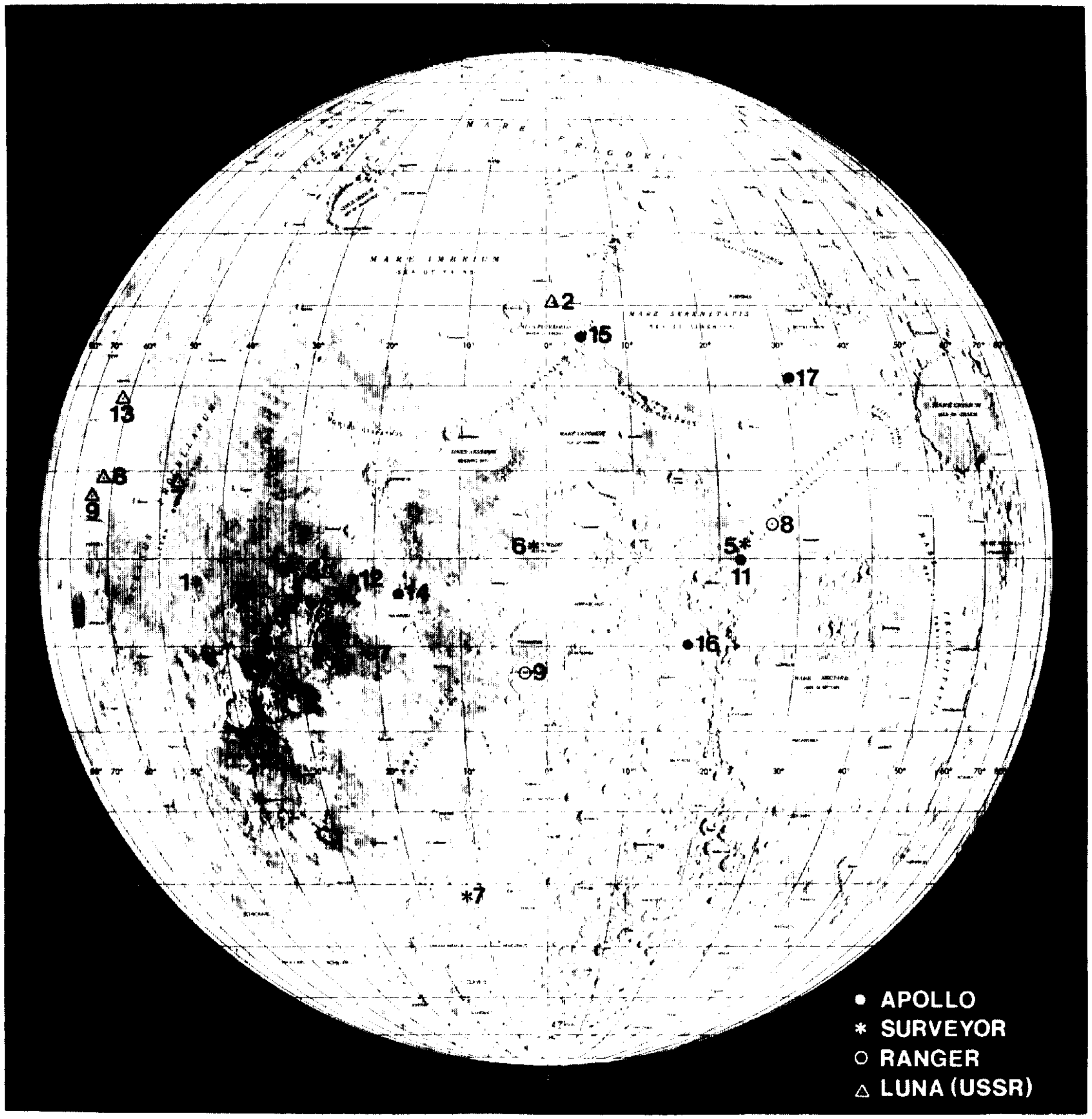


Chart of the lunar nearside showing prominent named features and landing sites for Apollo missions (U.S. Air Force chart LEM-1A).

Employing crater frequencies, geomorphology, color and albedo discussed in the last section, draw lines around what you believe could be different geologic formations on the photograph below. To assist you, some of the formations have been identified by letters.

In the space below, list the formations in their correct geologic (chronological) sequence, with the oldest formation at the bottom and the youngest formation or event at the top.

Formation		Characteristics	Possible origin
5	Youngest		
4			
3			
2			
1	Oldest		

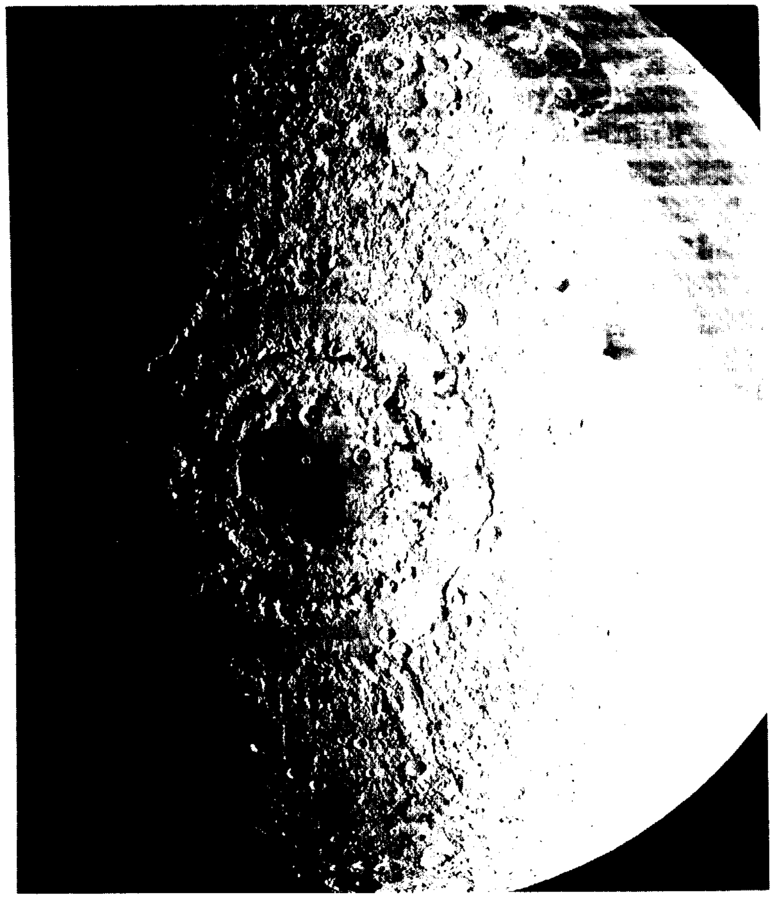
Photograph of the lunar crater *Gassendi* (125 km in diameter), located on the north edge of Mare Humorum (Lunar Orbiter 4, Frame 143).

MARIA, TERRAE, AND MOUNTAINS

Even to the most casual observer, the Moon can be subdivided into two distinct regions: a) light areas and b) dark areas. These areas were first described by astronomers in the 17th Century. They named the dark areas *maria* (literally, *seas*) and the light areas *terrae* (land, or *earth*) because they believed the areas corresponded to those on Earth. Although it was later realized that the dark regions are not water, the terms maria and terrae are still used.

Maria are given Latinized names to indicate imaginary conditions; for example, Mare Imbrium is the Sea of Rains, Mare Tranquillitatis is the Sea of Tranquillity. Maria are characterized as having a low albedo (dark appearance), relatively few craters, flat surfaces, different kinds of surface structures, relatively low elevations, and locations often in circular basins. The circular basins are believed to be large impact craters formed by the collision of the Moon with very large meteors or small planetesimals. Some of the basins were then filled, or partly filled, with dark lava flows composed predominantly of *basalt*, a volcanic rock common on Earth. Nearly all the circular basins on the frontside (side of the Moon that always faces Earth) are filled with mare material, whereas almost all the basins on the farside (side of the Moon that cannot be seen from Earth) are devoid of mare-filling. The cause of this distribution of maria has not been suitably explained.

In contrast to the maria, the terrae (or highlands) are heavily cratered with large, old-appearing craters, have rugged surfaces with high albedos (light appearance), and generally are higher in elevation than the maria. Mountain ranges constitute a subdivision of the lunar terrae. Nearly all the ranges are concentric to the circular basins (often forming the "rim" of the basins) and are probably directly related to the formation of the basins. The ranges are tens of thousands of meters long and often thousands of meters high. Most lunar mountain ranges are named after those on Earth, e.g. Jura Mts., Apennines, Alps.



Mare Orientale, a 900 km circular basin partly filled with dark, smooth mare material. At least three mountain ranges, each several thousand meters high, ring the basin. This enormous impact basin cannot be seen from Earth: it was photographed by Lunar Orbiter 4 (frame LO IV M-187).

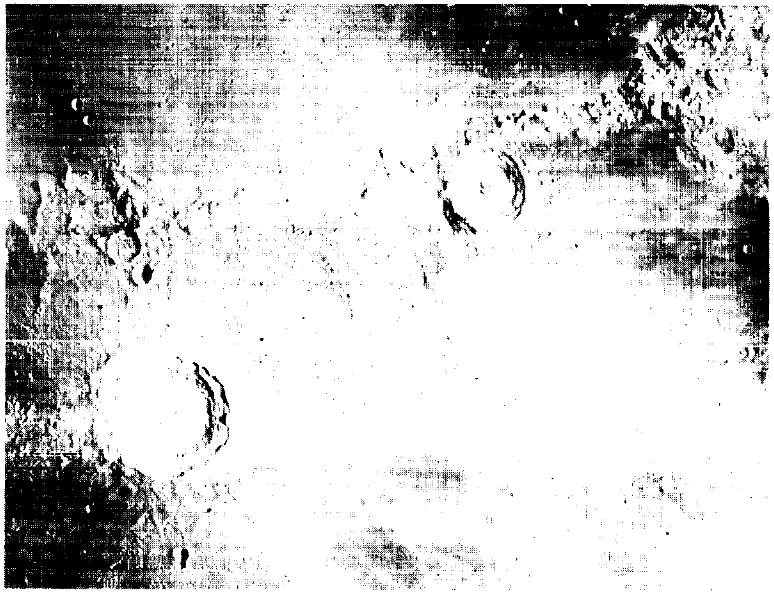
The Alpine Valley, a depression about 150 km long and 8 km wide, cuts across terrae and the Alpine Mountains toward Mare Imbrium at the top of the picture. A sinuous rille occupies the center of the valley (Lunar Orbiter 5 frame M-102).

CRATERS

Craters are the dominant landforms of both maria and terrae. For many decades selenologists were divided into two camps: those who believed that lunar craters were formed by internal processes, such as volcanism, and those who believed that the craters resulted from meteoritic impact. It is only recently that a better understanding of the cratering processes on the Moon has evolved. Most investigators agree that the vast majority of lunar craters are of impact origin; but not to the total exclusion of other kinds of craters. Volcanism also has played a significant role in shaping the lunar surface, including the formation of craters.

Most information on impact craters has been gained from research conducted within the last ten years. The effort has been a combination of laboratory experiments, field work, and photographic interpretation of lunar and terrestrial craters. These studies have shown that fresh impact craters can be identified by the following characteristics:

1. Usually very circular in outline;
2. Rock strata in the rims are overturned;
3. Crater floor is lower than the surrounding surface;
4. An *ejecta blanket*, composed of rock debris thrown out of the crater, surrounds the crater rim; it is thickest near the rim and thins to a feather-edge away from the crater;
5. *Secondary craters*, formed when blocks of ejecta strike the surrounding surface, are distributed radially from the crater, often in crater chains;
6. Formation of unique minerals, such as *coesite* and *stishovite* (forms of quartz); these minerals are known to form only by the intense shock of impact processes.



Crater Copernicus on the lunar nearside is about 90 km in diameter: its well-defined ejecta blanket and secondary craters identify it as a young impact crater (Lunar Orbiter 4 frame M-121).

Small volcanic crater on the basaltic Snake River Plain, Idaho: its 2 km diameter has been built of lava and ash deposits.

Most meteorites that form craters hit the surface at very high speeds—often more than 10 km per second (22,500 miles per hour)—breaking into smaller fragments and partly vaporizing during crater formation. Only for low-speed impacts is the meteorite buried beneath the crater. Craters formed by impact range in size from the mare-filled circular basins hundreds of kilometers in diameter to craters less than 10 microns in diameter (4/1000 of an inch). There are progressively more and more craters in the smaller size ranges on the Moon.

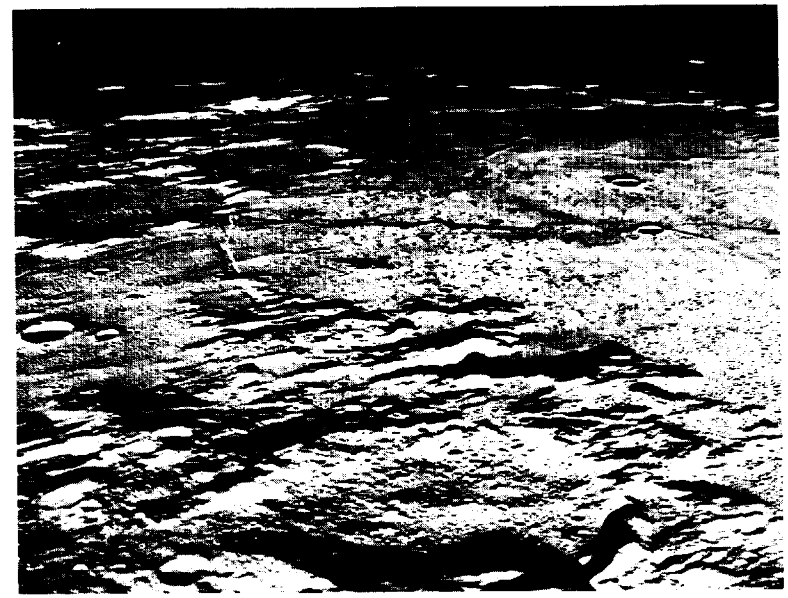
In contrast to impact craters, craters formed by volcanism are characterized as:

1. Generally without circular outlines;
2. Crater floor higher than surrounding surface;
3. Relatively small diameters;
4. Rims that are not overturned, but built up of lava flows and cinders;
5. Irregular zones of light and dark material in patches around the crater.

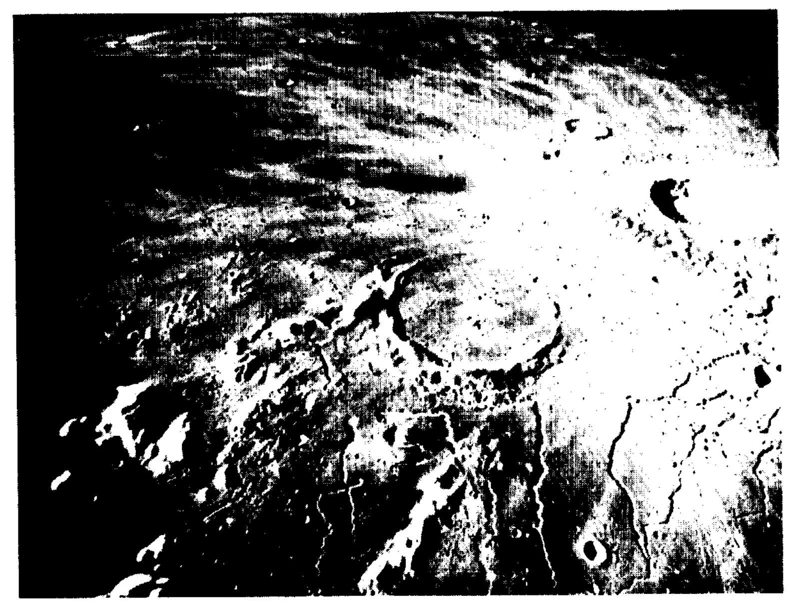
Some volcanic craters on Earth, however, appear very similar to impact craters. The characteristics listed for impact and volcanic craters are generalizations that do have exceptions.

RILLES

Rilles are channel-like depressions fairly common on the lunar surface. *Linear rilles* are large, relatively straight depressions often several kilometers wide and hundreds of kilometers long. They cut across crater rims, terrae and maria and are believed to be deep-seated structural features similar to *grabens* on Earth. Grabens are down-dropped blocks of land between two parallel faults that result from major adjustments in the crust. Owens Valley in California is a graben.



A typical linear rille more than one hundred km long on the lunar nearside: because linear rilles transect terrae and mare units they are believed to be structures similar to *grabens* on Earth – downdropped blocks between two parallel faults(photo from Apollo 10, frame 4856).



Sinuous rilles in the lunar Harbinger Mountains: mare-flooded crater at top of photograph is Prinz, about 45 km in diameter (photo from Apollo 15, metric frame M3-2606).

SINUOUS RILLES

Sinuous rilles usually are smaller than linear rilles, have a meandering course, and generally are restricted to the maria. They often appear to originate in irregular shaped depressions (volcanic vents?) and trend downslope across the maria surface, flowing around mountains and other high areas rather than cutting across them as in the case of linear rilles. Sinuous rilles may be discontinuous, may have cut-off branches, and often terminate with no visible feature at their end.

Most investigators believe sinuous rilles to be the result of fluid flow. Sharp controversy arises, however, as to the type of fluid involved. The diverse modes of origin proposed to explain sinuous rilles include:
1) erosion by water at a time when the Moon may have had surface water, 2) collapse of underground rivers, 3) erosion by ash flows, 4) fluidization of surface fragments by out-gassing through fractures in the lunar crust, and 5) lava channel and lava tube development associated with the mare basalts. Although there are difficulties with each hypothesis, many sinuous rilles seem best explained by the last proposal. Lava channels (depressions that carry molten lava from the eruption vent to the flow front) and lava tubes (channels that become roofed-over: these usually collapse within a few hundred years) are rather common in basalt flows on Earth and it is reasonable to assume that they would be present in basalt flows on the Moon.

DOMES AND CONES

Small rounded hills, or *domes*, and small angular peaks, or *cones*, are common on some mare and on some crater floors. They are usually less than 12 km in diameter and less than a few hundred meters high. Both kinds of structures probably result from igneous activity.

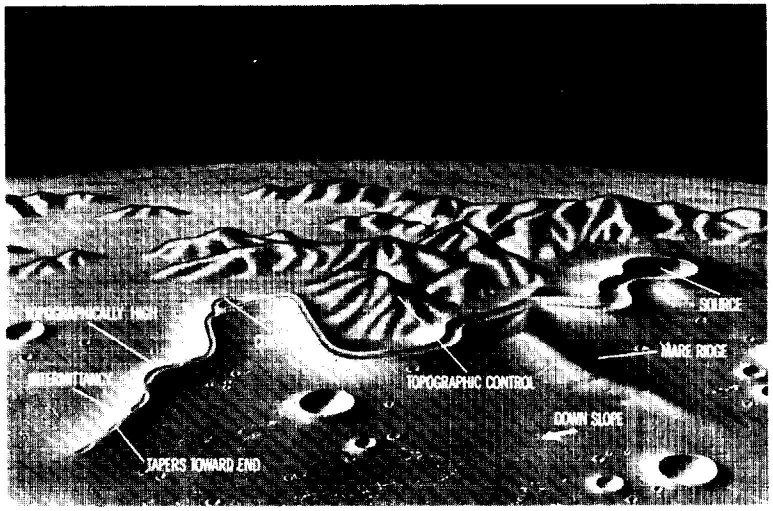


Diagram showing the characteristics of a typical lunar sinuous rille.

Volcanic crater and basaltic lava flow channel on the Snake River Plain, Idaho. This feature, and other similar structures, may be analogous to many lunar sinuous rilles. Both lunar and Earth features occur in basaltic lava.

Domes may be intrusive features (plutonic igneous activity) similar to *laccoliths* on Earth. Laccoliths are mushroom-shaped bodies of magma that may push the surface into a dome, but solidify before reaching the surface. Lunar domes with central craters may be combinations of intrusive and extrusive activities, the craters representing volcanism where parts of the magma pushed through to the surface.

The steep-sided cones may be entirely extrusive (volcanic) structures similar to cinder cones on Earth. These features are common on basalt flows and are the result of piles of cinders building around the vent. They often have small channels associated with them on both Earth and the Moon.

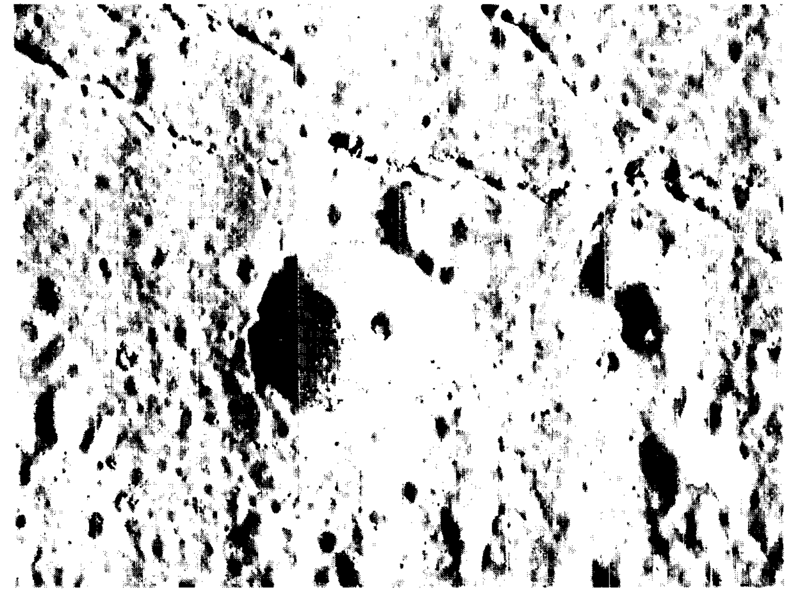
WRINKLE RIDGES

Wrinkle ridges are irregular, discontinuous features that extend tens of kilometers across maria surfaces. Many appear to consist of two parts, a broad, low, swelling superposed by a sharper, more narrow element. Total height above the maria seldom exceeds a few hundred meters. Wrinkle ridges are probably volcanic features associated with the mare filling of the basins. They may have formed by lava oozing through cracks in the crust of the basalt lava flow. However, there are no features similar to them on Earth for comparison.

FAULTS AND GROOVES

Many sharp, linear structures on the Moon are faults, or ruptures in the lunar crust along which there has been movement. The Straight Wall in the eastern part of Mare Nubium is an example of a probable lunar fault more than 100 km long, along which the east side has been raised several hundred meters above the west side.

Many of the circular basins have large scooped-out depressions which radiate from the basins. These may have formed in association with the ejecta immediately following the impact that created the basin. Grooves are particularly prominent around Mare Orientale.



Cinder cone on the floor of lunar crater Copernicus: this feature is about 600 m in diameter and is believed to have formed in association with other volcanic activity following the impact that created the main crater (photograph from Lunar Orbiter 5 frame H-154).

Cinder cone on the floor of the summit crater, Mauna Loa volcano, Hawaii: note the fracture that cuts through the cone, similar to the fractures on the floor of Copernicus.

LUNAR SAMPLES

Moon samples returned from Apollo lunar landings have yielded a variety of materials including: 1) crystalline rocks of *basalt*, *gabbro* and *anorthosite*, 2) glasses, 3) breccias and 4) soil. The crystalline rocks solidified from liquid melts which welled-up from beneath the surface. The basalts are fine-grained and contain vesicles, or holes, indicating that they formed from lava flows, whereas the gabbros are coarse-grained and probably cooled beneath the surface. Both rock types are composed predominantly of the minerals plagioclase, pyroxene and olivine, similar to basalts and gabbros on Earth. There are, however, some notable differences between lunar rocks and terrestrial rocks; for example, the lunar rocks from Apollo 11 contain a much higher proportion of titanium than any rocks known on Earth.

Small pieces of anorthosite have been found at the mare landing sites. Anorthosite is a white rock composed almost entirely of the mineral plagioclase and is less dense than basalt and gabbro. It is likely that the anorthosite was thrown into the mare regions from the light-colored terrae as ejecta from impact processes.

The lunar soil is composed of small fragments of basalt, gabbro and anorthosite, broken by the impact of countless thousands of meteorites. Mixed in the soil are small glass objects generally less than 0.2 mm in diameter. They are often spherical, but may also be dumbbell-shaped, ovoid, or angular. Colors may be red, brown, yellow, green or colorless. Chemically, they are similar to the basalt and gabbro and are believed to have formed when impacts on the lava surfaces melted some of the rocks. This melt was thrown out of the crater and cooled as glass blobs, or splashed on surrounding rocks as a glass-glaze.

Lunar breccias are composed of angular fragments of basalt, gabbro, anorthosite, glass, etc., compacted to form a generally soft rock. They are compacted by the shock-process of impact. Samples of breccia sliced into very thin sections show internal structure and the materials of which they are composed.

Absolute age-dating of lunar samples by radiometric techniques shows that some areas of the Moon formed 4.5 billion years ago, possibly coinciding with the age of the final stages of formation for the Solar System. Dates on the lunar lavas range from 3.2 billion years to 3.8 billion years, depending upon locality. These dates demonstrate that lunar volcanism extended over a long period and has been an important modifying process, along with meteoritic impact.

The Straight Wall, a long fault, or break in the lunar crust in the eastern part of Mare Nubium; the east (top) side has been uplifted several hundred meters in relation to the west side (Lunar Orbiter 4 frame H-113).

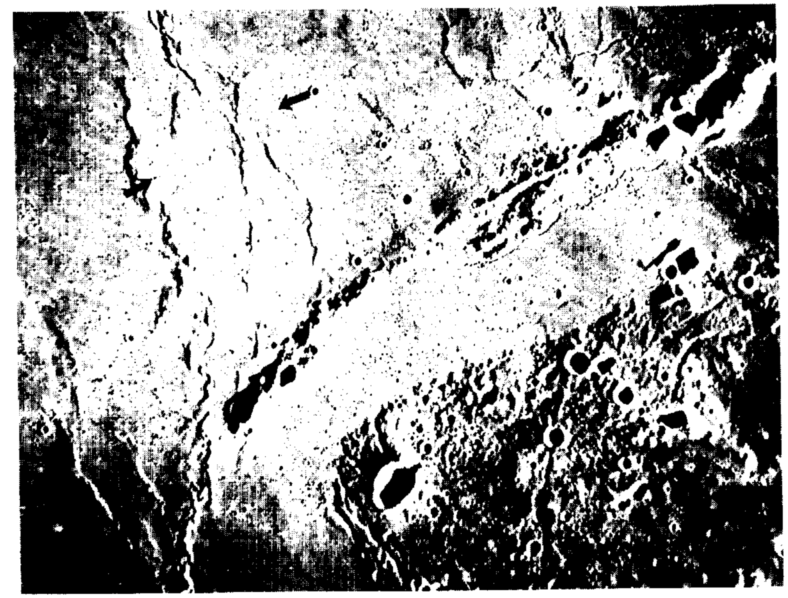
Section of lunar breccia to show internal structure and composition; angular fragments of rock and mineral grains have been compacted by impact processes to form the soft rock, breccia; 2 mm round object is a glass spherule (photograph courtesy of D. Stöffler).

GEOPHYSICS

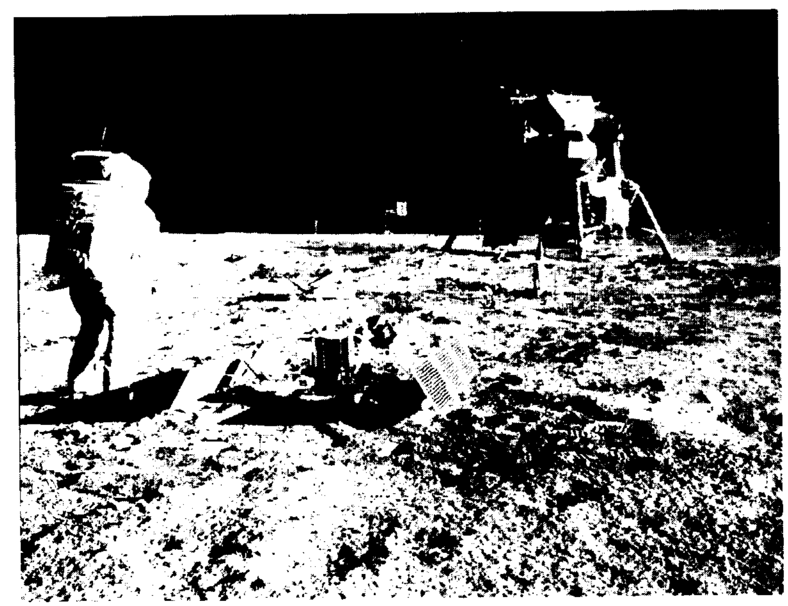
Moonquakes. Seismometers left at Apollo 12, 14 and 15 landing sites provide a network that allows accurate detection and location of "earthquakes" on the Moon. Results obtained to date show that there is at least one active seismic zone on the nearside, and that the time of greatest activity occurs when the Moon and Earth are closest. It is probable that the tremendous strains generated by the gravitational attraction between the two bodies are being released by shifting of crustal blocks of rock on the Moon, and perhaps the Earth as well.

Interior Temperatures. During Apollo 15, a hole was drilled into the lunar surface and an instrument was placed in it to measure the flow of heat from the lunar interior. Preliminary results show that the heat-flow is very high, being nearly the same as for Earth (proportional to the differences in size). This indicates that there may be zones of radioactive heating in parts of the lunar interior, similar to radioactive heating in the crust and upper mantle of the Earth.

Mascons. Analyses of the orbits of manned and unmanned spacecraft around the Moon show that the pull of gravity is not uniform on the Moon. Over some areas, there is an increase in the gravitational attraction for the spacecraft (the spacecraft speed up and are pulled toward the Moon over these areas). These areas coincide with some of the mare-filled circular basins and the gravity "highs" are believed to be the result of "mass-concentrations" (*mascons*) of high density material within the basins.



Wrinkle ridges (arrows), in eastern Oceanus Procellarum, may be structures that resulted from lava oozing through fractures in the lava flows filling in mare basins. Photo width is about 90 km (photograph from Apollo 15 metric frame M3-2485).



Astronaut Aldrin deploying seismometer at Apollo 11 landing site as part of geophysical experiment package (Frame AS11-40-5948).

PART IV Geology of Mars

INTRODUCTION

The techniques that were developed to study the geology of the Moon are now being used for Mars. Mars, however, is considerably more complex than the Moon. Each new mission to Mars has resulted in a revision of the ideas concerning the geology of the "Red Planet." Most information has been gained from unmanned *Mariner* spacecraft. In 1965 Mariner 4 transmitted the first close-up pictures of Mars and, although crude by current standards, the pictures revealed the presence of many large craters which led some investigators to believe that the martian surface was essentially the same as the Moon's surface. In 1969 Mariners 6 and 7 photographed about 10% of the planet and showed that, in addition to craters, other terrain types were present, including "chaotic" terrain (characterized by irregular, jumbled surfaces of unknown origin), possible desert regions composed of relatively flat, featureless surfaces, and polar regions containing irregular grooves, ridges, and pits.

Mariner 9 (1971–1972) provided the first comprehensive view of Mars, photographing the entire planet with high resolution cameras. Some areas, such as the receding polar caps, were photographed many times during several months in order to evaluate seasonal changes. An extremely successful mission, Mariner 9 has yielded more than 8000 pictures of the planet, as well as other types of data concerning the surface and atmosphere.

GEOLOGIC-GEOMORPHIC UNITS OF MARS

The major geologic units and terrain types of Mars include wind-blown deposits and structures, channels and canyonlands, "chaotic" terrain, circular basins, volcanoes, cratered terrains and structures associated with the polar regions. Because many of these structures and features are unique to Mars—totally unlike anything earthly or lunar—interpretations and theories of their geology are in the formative stages and it will be many years before the various ideas are resolved.

CIRCULAR BASINS

The circular basins on Mars are large depressions (some are more than 2000 km in diameter) similar to the impact-formed, mare-filled basins on the Moon, except that they are less well defined than the lunar features. As on the Moon, the martian basins appear to be among the oldest discernible features. However, unlike the Moon, which lacks an atmosphere (and hence, lacks surface erosion by wind, rain, snow, etc.), Mars has a thin atmosphere and the agents of gradation, particularly wind, are active. Thus, martian surface features are more degraded than similar features of equivalent age on the Moon.

One of the two "moons" of Mars, named *Phobos*, is about 25 km long x 21 km wide and is pock-marked with impact craters (Mariner 9 photograph).

Nix Olympica, the largest of several shield volcanoes in the equatorial zone of Mars, is more than 500 km wide at its base. At its summit is a complex *caldera*, about 64 km in diameter, formed by multiple collapse craters (mosaic of Mariner 9 photographs).

CRATERED TERRAINS

About 40% of the equatorial zone and much of the rest of the planet are covered with impact craters. Although the cratered area is much less than earlier estimates based on Mariner 4, 6, and 7 photographs, impact craters are the dominant landform on Mars. Cratered terrain is subdivided according to relative crater densities (from oldest to youngest): 1) densely cratered terrain, 2) moderately cratered terrain, and 3) cratered plains. Even the freshest martian impact crater (observed thus far), however, lacks the bright rays and secondary craters characteristic of fresh lunar impact craters. The degraded appearance of craters on Mars indicates active surface erosion.

VOLCANOES

One of the most spectacular discoveries of Mariner 9 was the existence of huge *shield volcanoes* in the martian equatorial zone. Similar in form to volcanoes making up the Hawaiian Islands (built by repeated eruptions of fluid basaltic lava), the martian shield volcanoes are nearly twice as large as their terrestrial counterparts. Individual lava flows and lava tubes can be seen on the flanks of *Nix Olympica*, the largest of the known martian shield volcanoes.

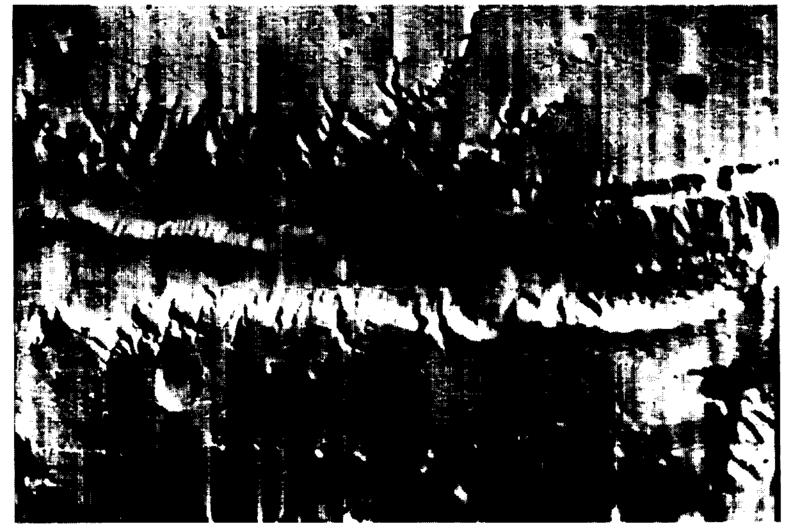
Other volcanic features observed on Mariner 9 photographs include steep-sided dome volcanoes, possible cone-craters, and sheet flows similar to the lunar Imbrian Flows.

CANYONLANDS

Equally surprising is the martian "grand canyon." A vast trench that in places is more than 2 km deep and 125 km wide, it extends more than 4500 km along the equator. At its western end, it grades into a terrain marked by networks of intersecting graben-like structures and chains of pit craters. The eastern end of the canyonlands grades into "chaotic" terrain, characterized by structures resembling huge landslides. Side canyons and tributaries of the main canyon resemble landforms eroded by water. However, many of the basins within the canyon are closed and some account must be made for the volume of eroded material. Although the origin is highly speculative, the canyonlands may have been formed primarily by structural down-warping or down-faulting with subsequent modification by gradation.

POLAR REGIONS

The northern and southern polar regions have been of great interest to martian investigators. As the martian summer advances, the polar caps retreat. If a significant part of the polar ice is frozen water, then perhaps the margin of the receding ice cap would be a favorable habitat for martian life. Preliminary results from Mariner 9 indicate that the south ice cap is composed of water ice overlain in the winter by carbon dioxide ice. Thus, perhaps this region is a favorable landing site for *Viking* spacecraft (unmanned martian lander, 1976), with its life-detection instruments. Engineering constraints, however, may require a landing in the equatorial zone.



Part of the martian "*Canyonlands*" in the equatorial zone. Many of the side canyons appear to have been partly eroded by fluids, perhaps water. The parallel chain of craters along the southern side of the canyon may have formed by collapse, or by volcanic explosions. This picture covers an area about 375 km x 480 km (Mariner 9 photograph).

The "*Chandelier*" at the western end of the canyonlands. This and similar features in this region appear to be networks of grabens (parallel faults with central down-dropped blocks). This picture covers an area about 540 km x 425 km (Mariner 9 photograph).

"*Laminated*" terrain of the southern polar region. The bands visible along the smoothly sculptured hill may be horizontal alternating layers of dust and ice (water ice and/or carbon dioxide ice). This picture covers an area about 46 km x 59 km (Mariner 9 photograph).

The black streaks associated with many of the craters shown in this Mariner 9 photograph are believed to be *eolian* (wind-blown) features. Light and dark streaks, usually found with craters, have been observed over vast regions of Mars. The two largest craters are about 29 km in diameter.

The polar regions contain several diverse structures and terrain types. Among the most startling is the *laminated terrain*. This unit is characterized by narrow, evenly spaced bands along smooth hillsides. The bands are thought to be the edges of horizontal, alternating layers of ice (water and/or carbon dioxide) and wind-blown dust.

Pitted plains occupy large parts of the polar regions. In this unit, smooth plains are indented with irregular pits and small bowl-shaped impact craters. The pits may have been formed by subsurface removal of material (by an unknown process) and subsequent collapse of surface material.

WIND-BLOWN FEATURES

Probably the youngest surface features on Mars are those formed by *eolian* (wind) processes. When Mariner 9 first arrived at Mars, one of the largest dust storms of the century was raging over the planet. It became apparent that wind is one of the most prominent agents of gradation on Mars. Sand dunes and light and dark "tails" associated with craters have been identified as eolian landforms.

Several years will be required for U.S. Geological Survey, University, and NASA geologists to reduce the tremendous wealth of data returned by Mariner 9. Geologic mapping programs, studies of individual terrain types and structures, geologic investigations of terrestrial terrains for comparisons with Mars, and laboratory studies are leading to an understanding of the complex geology of Mars.

Conclusions

This brief and superficial account of lunar and planetary geology has been intended to aquaint the reader with the techniques employed in this rather new field of science.. But more importantly, the intent was to create an awareness of geologic processes, not only on other planets but on Earth as well, so that a better understanding can be gained of "our place in the Sun."

Appendix A: Sources of Information and Material

A. *General geology*

Leet, D. L. and S. Judson, 1971. *Physical Geology*, Prentice Hall, Inc. Englewood Cliffs, New Jersey, 4th ed. Excellent college-level text book; includes preliminary geological results of Apollo 11 and 12 and a discussion of the origin of the Solar System. $12.00

Dott, R. H. and R. L. Batten, 1971. *Evolution of the Earth*, McGraw-Hill Book Co., San Francisco. College-level text book of the geologic history of the earth. $13.00

Wyckoff, Jerome, 1960. *The Story of Geology*, Golden Press, New York, 177 p. Elementary school-level introduction to geology; well illustrated with colored diagrams and photographs. $6.50

B. *Lunar and Planetary Geology Text Books*

Fielder, G., ed., 1971. *Geology and Physics of the Moon*, American Elsevier Publ. Co., New York. A collection of papers on different aspects of lunar geology. $25.50

Mutch, T. A., 1972 *Geology of the Moon*: A stratigraphic view. Princeton University Press, Princeton, New Jersey. College-level text and reference, well written and illustrated. Extensively revised from the 1970 first edition. About $20.00

Short, N. M., 1972 (expected). *Planetary Geoscience*, McGraw-Hill Book Co., San Francisco. College-level text book and laboratory manual; well illustrated; includes sections on meteorites, terrestrial impact craters, the solar system, and the terrestrial planets.

C. *Reference Books and Papers*

Carr, M. H., ed. 1970. *A strategy for the geologic exploration of the planets*, U.S. Geological Survey Circular 640. Free from U.S. Geol. Survey, Washington, D.C. 20242. General account of the methods and rationale of planetary geology.

Davies, M. E. and B. C. Murray, 1971. The View from Space, Columbia Univ. Press, New York. College-level reference on lunar and planetary spacecraft that carried imaging systems. Excellent review of advantages and disadvantages of different systems. $14.95.

Kosofsky, L. J. and F. El-Baz, 1969. *The Moon as Viewed by Lunar Orbiter*, NASA SP-200. An excellent collection of annotated lunar photographs from the Lunar Orbiter series. *GPO $7.50

Lowman, P. D., 1969. *Lunar Panorama*, Pulb. Weltflugbild, R. A. Muller-Feldmeilen, Zurich, collection of lunar photographs from unmanned missions, with annotations of the geology. $12.45

Whipple, F. L., 1968. *Earth, Moon and Planets*, Harvard Univ. Press, Cambridge. Excellent general treatment of the solar system; very little geology. Paperback edition, $3.00.

Wilhelms, D. E., 1970. *Summary of Lunar Stratigraphy-Telescopic Observations*, U.S. Geological Survey Professional Paper 599-F. 47 p. Good account of the methods of lunar geologic mapping. *GPO 60¢

D. *Atlases of lunar and planetary photographs*

Alter, Dinsmore, 1967. *Pictorial Guide to the Moon*, Thom. Y. Crowell Co., New York, 199 p. Primarily an atlas of telescopic photographs with an extensive text. $8.95

Appendix A (continued)

Alter, Dinsmore, ed., 1964. *Lunar Atlas*, Dover Publications, Inc., New York. Collection of telescopic lunar photographs. 154 plates. Paper back $6.00.

Bowker, D. E. and J. K. Hughes, 1971. *Lunar Orbiter Photographic Atlas of the Moon*, NASA SP-206 (675 plates). Collection of selected Lunar Orbiter photographs. *GPO $19.25

Collins, S. A., 1971. *The Mariner 6 and 7 pictures of Mars*, NASA SP-263, 159 p. Complete collection of photographs with a short explanation of the missions. *GPO $4.25.

Cortwright, E. M., 1968. *Exploring Space with a Camera*, NASA SP-168, 214 p. Collection of the best space photographs taken until the publication date; includes scenes from Gemini (of Earth, in color), Ranger, Surveyor, Lunar Orbiter, with descriptions of the spacecraft and missions. *GPO $4.25

Musgrove, R. G., 1971. *Lunar Photographs from Apollos 8, 10, and 11*, NASA SP-246, 119 p. Selected photographs from the earliest manned lunar missions; some pictures in color. *GPO $4.00

E. *Public information bulletins on lunar and planetary missions*, informative, well written and illustrated; excellent teaching materials. Available from *GPO

Lunar Orbiter, NASA Facts-32/ vol. 4, no. 4 15¢
The view from Ranger, NASA EP-38 40¢
Journey to the Moon, NASA Facts-40/11-67 (wall chart) 30¢
Log of Apollo 11 (first lunar landing), NASA EP-72 35¢
The first lunar landing, as told by the astronauts, NASA EP-73 75¢
Mariner Spacecraft, NASA Facts-39/2-68 20¢

F. *Maps and charts*

The Earth's Moon, 1969. National Geographic Society, Washington, D.C. 20036, $1.00. 40″ x 27″. Nearside and farside, with index to named features; information on lunar shape and motion on the margins; the best general lunar chart available.

Wilhelms, D. E. and J. K. McCauley, 1971. Geologic Map of the nearside of the Moon, U.S. Geol. Survey Map I-703, 54″ x 36″ *GPO $1.00

Lunar Chart LEM—frontside. Available in three scales from *GPO:
66″ x 66″ (1:2,500,000 scale) two sheets, $2.00
35″ x 36″ (1:5,000,000 scale) $1.00
19″ x 17″ (1:10,000,000 scale) $0.50

Lunar Chart LPC-1 Frontside, backside, and polar regions, 1:10,000,000 38″ x 26″, *GPO 50¢

G. *Photographs*—most of the following agencies and institutions will supply indices of available photographs, with prices, on request.

Public Affairs Office, Ames Research Center, National Aeronautics and Space Administration, Moffett Field, California, 94035.

National Space Science Data Center, Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Maryland, 20771. Source for photographic prints and negatives of research quality for Lunar Orbiter, Surveyor, Apollo, Mariner, etc. missions. Individual catalogs for missions are available. Photographs are supplied at cost.

Observatory telescopic photographs of the Moon, planets, and stars:

Lick Observatory, Univ. of California at Santa Cruz, Santa Cruz, Calif. 95060

Hale Observatories, Calif. Inst. Tech. Bookstore, 1201 E. California Blvd., Pasadena, Calif. 91109. Also sells NASA photographs from Apollo, Surveyor, Ranger, and Mariner missions.

Yerkes Observatory, Williams Bay, Wisconsin, 53193. 35¢ for a catalog.

H. *Motion Pictures*

NASA film catalog-available from Ames Research Center, NASA, Moffett Field, Calif. 94035. Films are available free to bonafide representatives of educational, industrial, professional, youth activity and governmental organizations for group showings.

U.S. Geological Survey-Astrogeology Branch films-listing is available from The Information Office, Geological Survey, Washington, D.C. 20242.

*GPO = Superintendent of Documents, Government Printing Office, Washington, D.C. 20402

Notes

GPO 793-624